Echo in the effective field of a multipulse NQR train

V. L. Ermakov, R. Kh. Kurbanov, D. Ya. Osokin, and V. A. Shagalov
Physicotechnical Institute of General Physics, Academy of Sciences of the USSR, 420029, Kazan

(Submitted 23 July 1991)
Pis'ma Zh. Eksp. Teor. Fiz. **54**, No. 8, 464–466 (25 October 1991)

Induction and echo signals have been seen for the first time in the effective field of a multipulse NQR train. It has been demonstrated experimentally that these effects can be utilized for NQR tomography.

The effect of pulsed rf fields on a spin system can be thought of as the effect of a constant effective field in a rotating coordinate system.[1] In other words, during the application of pulses one can introduce an effective coordinate system which is determined by the pulses and the detuning. The *z* axis of this coordinate system runs along the direction of the effective field. It has been shown previously[2] that the time evolution of the "transverse" component of the initial density matrix is analogous to an induction signal in this new coordinate system. In the present letter we report the first experimental results on a reversal of the magnetization decay due to a nonuniformity of the effective field in the effective coordinate system. We propose some possibilities for utilizing these effects in nitrogen-14 NQR tomography.

We consider a quadrupole system of $J = 1$ spins in a zero magnetic field (the electric field gradient is asymmetric). We assume that the system is illuminated on one of three transitions. The experiments can be described with the help of operators with a fictitious spin[3] (1/2) which correspond to one transition. The commutation relations of these operators are completely equivalent to the ordinary commutation relations of the Cartesian components of a spin operator. For simplicity, we will thus omit the superscript which specifies the illuminated transition for the symbols for the fictitious-spin operators.

We consider a train $(\pi/2)_x - (\tau - \alpha_x - \tau)^n$. In contrast with ordinary pulsed spin locking, the initial magnetization in this case is perpendicular, rather than parallel, to the rf field. The Hamiltonian of the effective field of the detuning and the pulses[1] for short cycles ($t_c = 2\tau$) is $\mathscr{H}_e \approx \omega_e J_1$, where $\omega_e = \alpha/t_c$ is the precession frequency in the effective coordinate system.

The evolution of the initial density matrix $\rho_0 = J_2$ (some factors and terms unimportant to this discussion are being omitted) is determined by the expression

$$\rho(t_e) = \exp(-i\mathcal{H}_e t_e)\rho_0(\text{h.c.}) = J_2 \cos\omega_e t_e + J_\varsigma \sin\omega_e t_e .$$

The "effective" time t_e here has the meaning that observations are carried out only at discrete times $t_e = nt_c$.

We find an expression for the signal from the entire sample by taking an average over the spread of rotation angles α which exists in an actual experiment. To reach a qualitative understanding of the experiments, we assume that the real rotation angle is of the form $\alpha(1+\delta)$, where δ is a normally distributed random quantity with a zero mean and a standard deviation σ. The induction signal in the effective coordinate system is then determined by the integral

$$S(t_e) \sim \int_{-\infty}^{+\infty} \exp(-\delta^2/2\sigma^2)\mathrm{Sp}[J_2\rho(t_e)]d\delta \sim \exp(-\frac{1}{2}\sigma^2\bar{\omega}_e^2 t_e^2)\cos\bar{\omega}_e t_e.$$

Here $\bar{\omega}_e = \overline{\alpha(1+\delta)/t_c} = \alpha/t_c$ is the mean value of the effective field. A refocusing of the magnetization decay in the effective coordinate system can be achieved through the following modifications of the pulsed-spin-locking train:

1. Add an "extra" π pulse, $(\pi/2)_x - (\tau - \alpha_x - \tau)^N - \pi_y - (\tau - \alpha_x - \tau)^n$.

2. Change the sign of the effective field, $(\pi/2)_x - (\tau - \alpha_x - r)^N - (\tau - \alpha_{-x} - \tau)^n$.

After some straightforward calculations we find that there is an echo signal at the time $t_e = 2T_e$, where $T_e = Nt_c$, in each case:

$$S_{echo}(t_e) = \exp[-\frac{1}{2}\sigma^2\bar{\omega}_e^2(t_e - 2T_e)^2]\cos[\bar{\omega}_e(t_e - 2T_e)].$$

Figures 1 and 2 show the induction and echo signals found experimentally.

It was recently proposed[4] that the gradient of an rf field, rather than that of a

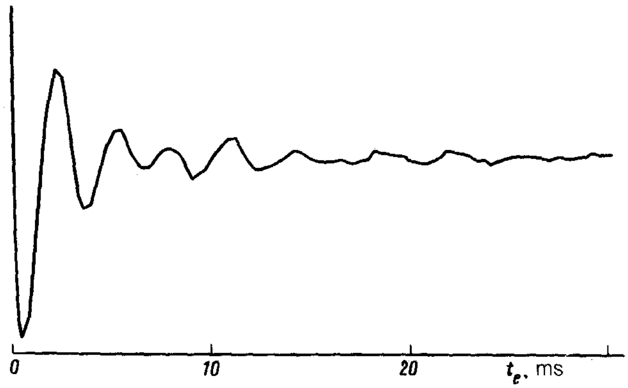

FIG. 1. Induction signal in the effective coordinate system for a pulsed-spin-locking train with $t_c = 0.6$ ms and $\alpha = 0.27$ rad (all the experiments were carried out on a $NaNO_2$ single crystal at 77 K at a frequency of 4.93135 MHz, which corresponds to the nitrogen-14 resonance).

constant field, be used for NQR tomography. In other words, the spatial positions of the spins would be coded in the value of the magnetization rotation angle, which is directly proportional to the amplitude of the rf field. This idea is particularly important for integer spins, since the use of gradients of a constant field is ineffective in this case. The reason is the "freezing" of the interaction of the quadrupole spin system with weak constant fields.[5]

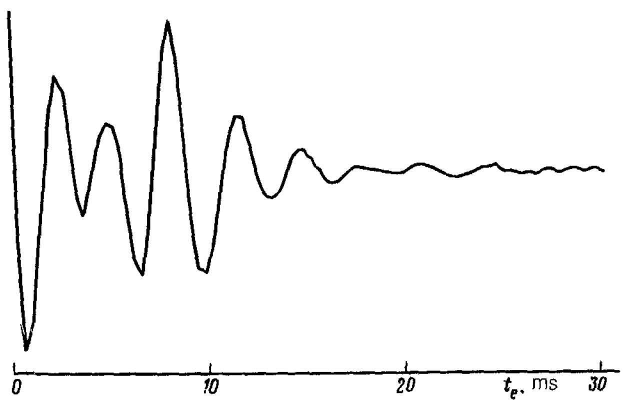

FIG. 2. Echo in the effective coordinate system upon a change in the sign of the effective field of the pulsed-spin-locking train at the time $T_e = 6.6$ ms.

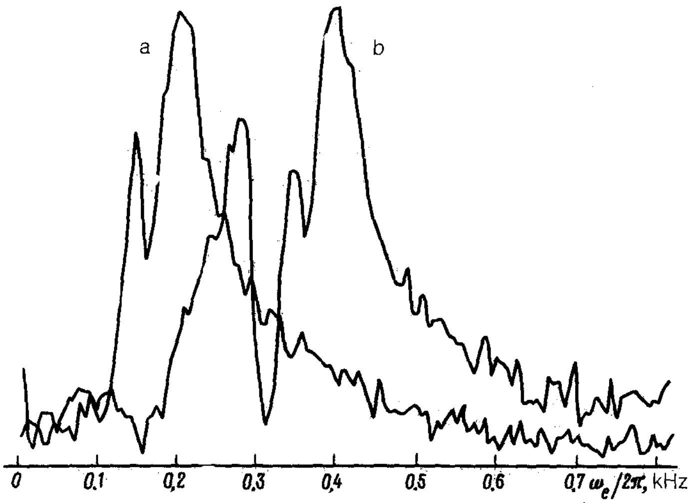

FIG. 3. Fourier spectra of the induction signals in the effective coordinate system for a pulsed-spin-locking train for various rotation angles, drawn to a common frequency scale. a—$\alpha_1 = 0.27$ rad (the induction signal itself is shown in Fig. 1); b—$\alpha_2 = 0.81$. Clearly, different rotation angles of the pulses in the train give rise to lines at different frequencies (a discussion of the line splitting found experimentally goes beyond the scope of this letter).

The results presented above could be used to develop this coding method further, and the rotation angle could in turn be coded in the carrier frequency of the induction and echo signals in the effective coordinate system. A Fourier transformation of the resulting data would then make it a simple matter to separate by frequency the signals from the spins with different spatial vectors. Figure 3 shows the results of an experimental demonstration of the feasibility of a practical realization of this approach for NQR tomography. The possibility of obtaining echo signals means that the sensitivity of the method could be raised. This advantage is particularly important for nitrogen compounds with weak signals.

[1]G. E. Karnaukh, B. N. Provotorov, and A. K. Khitrin, Zh. Eksp. Teor. Fiz. **84**, 161 (1983) [Sov. Phys. JETP **57**, 93 (1983)].
[2]D. Ya. Osokin, *Radio-Frequency Spectroscopy of Condensed Media*, Nauka, Moscow, 1990.
[3]S. Vega and A. J. Pines, Chem. Phys. **66**, 5624 (1977).
[4] E. Rommel, P. Nickel, R. Kimmich, and D. Pusiol, J. Magn. Resonance **91**, 630 (1991).
[5]G. W. Leppelmeier and E. L. Hahn, Phys. Rev. **141**, 724 (1966).

Translated by D. Parsons